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NATIONAL GAS TURBINE ESTABLISHMENT

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MEMORANDUM No. M.127

A TEST TO ASCERTAIN THE TURBINE BLADE TEMPERATURE PROFILES ON A W2/700 ENGINE USING DIRECT WATER SPRAY COOLING

by

K.R.F.KENWORTHY

SEPTEMBER, 1951

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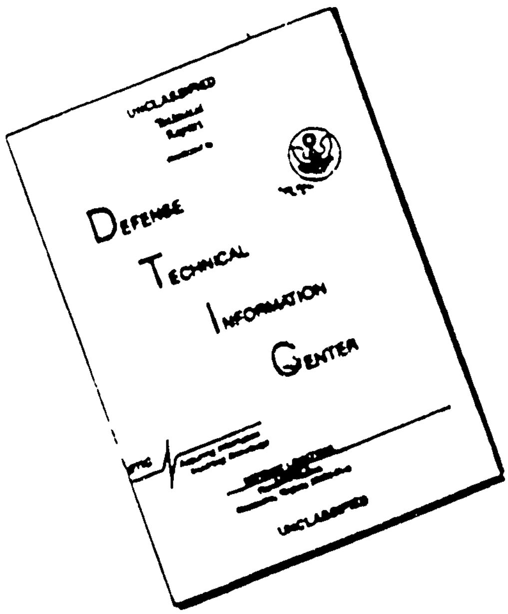

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A Test to Ascertain the Turbine Blade Temperature Profiles on a W2/700 Engine using Direct Water Spray Cooling

- by -

K.R.F. Kenworthy

SUMMARY

Considerable information has been obtained with this method of cooling in a W2/700 engine on the spanwise distribution of temperature in the turbine blades. Previous reports have recorded the changes in temperature at nominal 50% chord at several radial stations.

In order to investigate further the temperature distribution, both spanwise and chordwise, a series of tests was made using "indicator" blades of Silver Steel in the hardened condition. By running the blades in the engine they were tempered according to local temperature conditions and hence by using the hardness/temperature relationship of the material the temperature distribution over the whole of the blade surface was determined. Engine speed was limited to 15,000 r.p.m. from stress considerations.

The tests have shown that with a flow of water, sufficient to reduce the leading edge temperature by 300°C, the trailing edge is at temperature approximately 100°C higher.

By suitable disposition of the water jets it should be possible to achieve uniform cooling, if required, along the length of the blade within 100°C.

Under normal running conditions at 15,000 r.p.m. without cooling the variation across the chord is less than 60°C.

Memorandum No. M.127

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1.0 Introduction

To conclude the series of tests on the W2/700 engine using direct water spray for turbine blade cooling, a complete blade surface temperature patternation was required. Three alternative methods presented themselves for obtaining this information:-

(a) The extensive use of thermocouples and slip rings

(b) The use of thermo-sensitive indicator paints

(c) The use of thermo-indicator materials

There are objections to all methods and finally (c) above was chosen for the following reasons. The use of thermocouples would entail far more tappings than could be at present used with existing slip ring pick-ups. If thermo-sensitive paints were used then a painted pilot rake complete with appropriate thermocouples would have to be fitted, before and after the turbine, to correlate colour/temperature changes, and in addition, the inclusion of water in the gas stream was an unknown factor in relation to the sensitivity of the paints, also it was believed that the water would tend to remove some of the paint. This left thermo-indicator materials as a possibility. In this connection some experience had been gained, using Treble Super Monarch, Durehete and Silver Steel in pellet form for different temperature ranges, and obtaining the temperature from their respective hardness/temperature relationships. To obtain the maximum information, it was intended to use blades made of each of these materials, as between them practically the whole range from 200°C to 750°C could be covered. On rig testing, however, it was found that Silver Steel was the only material suitable from strength considerations. The Treble Super Monarch and Durehete were incapable of being run under centrifugal loads corresponding to their appropriate hardness/temperature ranges. Silver Steel was also subject to limitations as the following table will indicate.

Temperature °C	Stress Tons/sq.in.	Elongation
450	12.5	1% after $2\frac{1}{2}$ hrs.
450	15.0	1% after $1\frac{1}{4}$ hrs.
450	6.0	1% after 4.6 hrs.
500	12.5	16.26% after 10 hrs.

The composition of the Silver Steel used was as follows:-

Carbon	.95 to 1.05
Sulphur	.025
Silicon	.03 (Max)
Nickel	.15
Chromium	.10
Manganese	.15 to .25
Phosphor	.020

The centrifugal stress in the W2/700 turbine blade is 12.5 Tons/sq.in. at 16,750 r.p.m. at a blade temperature, in the high stress region, of 780°C. This meant that the blades could not be run at full speed except possibly under maximum cooling conditions. The tests were therefore done at conditions giving 9.1 Tons/sq.in. and 600°C, corresponding to a speed of 15,040 r.p.m. at 500°C jet pipe temperature. It was anticipated that a no-water condition could be obtained at this speed as a basis for comparison.

2.0 Method

The blades were made by standard procedure from 2 x 1 in. Silver Steel bar (all pieces for machining being obtained from the same forging) and machined from the solid, the material being worked in the soft condition to final dimensions. The blades were hardened in their finished polished state by water quenching from 760°C followed by a low temperature temper of 175°C for 15 minutes in an endeavour to eliminate cracking. This unfortunately was not completely successful and a wastage of some 40% was incurred due to surface cracks, mostly in the high stress region, owing to the sharp changes in section. Oil quenching was also tried but resulted in the blades not having the required hardness. Twelve blades were finally accepted for testing and a calibration of temperature versus hardness was obtained from the remaining unserviceable blades. Some variation of the hardness readings was anticipated on account of the non-uniformity of the blade section. Under the conditions of test i.e. 30 minutes at a steady temperature, it was found that the hardness reading near the thick root was about 20 points V.P.N. higher (about 12°C lower) than that near the tip for the lower temperature range. At the higher temperatures the discrepancy was less.

The blades were finally hand polished and hardness checked ready for running. One blade was mounted in the turbine disc for each test, but before installation the tip was ground down (with ample coolant) to allow for any elongation which might occur, and tests were done with varying water flows from a maximum of 797 lb/hr. at an engine speed of 15,040 r.p.m. and 500°C jet pipe temperature. In this way, by starting at the high water flow end of the range a check on the growth of the blade could be made and, as the quantity of water was reduced, the tip could be ground accordingly. The blade elongation was not measured, as is usual practice, over two datum centre points owing to the risks of failure due to cracks extending from the indentations, consequently measurements were made "overall" (dimension "L" Fig. I) and the elongation is referred to on this length throughout. The curves given in fig.8 do not therefore represent true strain. Ten tests were made at 15,040 r.p.m. and 500°C jet pipe temperature and two at 14,000 r.p.m. and 480°C jet pipe temperature, the latter to check on change in temperature profile.

Each test consisted of a run of 30 minutes from the on-speed conditions. The blades were given the equivalent of an air quench as shut down as water (when used) and engine were shut down simultaneously, the latter on the H.P. cock.

The mean combustion outlet temperature calculated from jet pipe and turbine temperature drop conditions for 15,040 r.p.m. was 620°C.

The water injection system was similar to that used in previous tests (Ref. 1 and 2). Water was fed to the inner ends of four equally spaced nozzle guide vanes and ejected from three small tubes in the trailing edges of each.

After each run the blade was removed from the engine and again hand polished and marked off by means of a special jig and template, as indicated in Fig. 1 ready for hardness checking. The blade was then mounted in a jig for this operation and hardness readings taken, using a Vickers Pyramid machine, with a 30 kilogramme load, on each surface of the blade.

In Fig. 1 it may be noticed that the spanwise stations on the concave side of the blade are offset to those of the convex side. This was done so that V.P.N. readings made at the thinner section of the blade (leading and trailing edges and tip) would not be affected due to thinness of section or proximity of indentations on the reverse side (centre of impressions to be $> 2\frac{1}{2}$ times the diagonal from any edge, and thickness under test should be $> 1\frac{1}{2}$ times diagonal of impression).

3.0 Discussion

It will be appreciated from the number of V.P.N. readings required in Fig.1 that a considerable mass of figures could be presented. To keep this note within a reasonable size only the plottings of five of the blades run at 15,040 r.p.m. are presented. The other blades fell into the general pattern and the two blades run at the lower speed had correspondingly reduced temperature profiles.

Figures 2 to 6 show the temperature profiles and water flows. This method of presentation has been chosen so that an overall picture of the blade temperature distribution may be easily seen. The measuring stations are shown equally spaced for clarity, the actual locations being indicated as percentages of chord and height. The temperature at any point is plotted vertically to the scale of 1 inch = 100°C. The chord line and blade height (Fig.2) representing a datum of 200°C on each figure. Thus all vertical ordinates are measured values above 200°C.

In the uncooled condition (Fig.2) it may be seen that there is very little temperature gradient across the chord at any blade height except near the tip where the trailing edge is at a higher temperature by approximately 59°C (leading edge 424°C, trailing edge 483°C) on the concave side and 28°C (leading edge 444°C, trailing edge 472°C) on the convex side. This is in general agreement with Ref.3 although R.P.M. and temperature conditions are higher than those presented in this note (16,750 R.P.M. and 650°C Jet Pipe Temperature) and results are not directly comparable.

Fig.3 shows the effects of passing 206 lb/hr. of water and the large drop in temperature (208°C) near the root leading edge on the convex side is apparent. This temperature drop is not so noticeable on the concave face, but it should be borne in mind that the stations are differently located on the two sides.

The remaining curves show the further extension of the cooled area of the blade with increased coolant flow, but it would appear that little cooling is being contributed by the outer discharge tubes (i.e. near tip). This is attributed to the pressure gradient across the turbine annulus and to the resistance to flow of the feed water. This effect is especially noticeable at the lower water pressures.

In all cases the convex sides of the blades are cooled to a greater extent than the concave. On Fig. 10 may be seen typical water marks on a Silver Steel blade which has run at a water flow of 185 lb/hr. This water patternation on the convex side is typical of all water flows and indicates the centrifuging of the water along the blade from the root. From the marks on this illustration it would be expected that towards the tip there would be a cooled region up the blade extending from the root leading edge towards the tip centre chord. This is confirmed by the temperature profiles of the convex side of the blades at the higher flow rates. Fig.6 is an example of this and shows the drop in temperature towards 50% chord nearer the tip.

Fig.7 shows the temperature of the convex and concave sides of the blade at 50% chord taken from the respective curves in Fig. 2 to 6 and shows more clearly the temperature difference through the blade section at any blade height.

As already noted, before running the blade tips were ground down to allow for possible growth and Fig.10 shows, approximately full size, the difference between a blade before and after running. This particular blade had been run for 30 minutes at 15,040 r.p.m. with a water flow of 185 lb/hr. and shows the "necking" which occurred and the resultant elongation. A plot of this elongation with varying water flow for all blades used in the test series is shown at Fig.9. The elongation of the blades probably results in some initial work hardening but this is relieved, to some degree, due to the operating temperature. This effect will be investigated in the near future.

The extent to which the temperature distribution is influenced by the thermal conductivity of the metal has not been determined. It is not considered however that the difference in this property as between Silver Steel and a typical blade metal such as Nimonic 80 would materially affect the results.

4.0 Conclusions

It is shown that the overall temperature of the turbine blades may be considerably reduced by the direct water spray method of turbine blade cooling. Owing to the nature of the cooling some considerable temperature gradient may be expected across the chord and along the span at the lower water flows. Towards the higher flow ranges this effect is less marked and cooling becomes more even.

The tests have also shown that with a flow of water, sufficient to reduce the leading edge temperature by 300°C, the trailing edge is at a temperature approximately 100°C higher.

By suitable disposition of the water jets it should be possible to achieve uniform cooling along the length of the blade within 100°C or to vary the degree of cooling, if required, subject to this limitation.

Under normal running conditions at 15,040 r.p.m. without cooling water, the variation across the chord is less than 60°C.

The tests have also shown that a substandard material such as Silver Steel is capable of being used in a turbine for short periods if adequately cooled.

Acknowledgment

The writer wishes to acknowledge the valuable and tedious work, which has been done by Misses Haines and Norman in reading and transcribing the results.

REFERENCES

No.	Author	Title etc.
1	K.R.F. Kenworthy	Preliminary tests to investigate Turbine Blade Cooling by Direct Water Spray. Memorandum No. M.75.
2	K.R.F. Kenworthy	Further tests on a W2/700 engine with water spray cooling of the turbine blades. Memorandum No. M.1[illegible].
3	E. Glenny	The use of hardened steel pellets for the measurement of temperatures attained by turbine rotor blades during service. Memorandum No. M.97.

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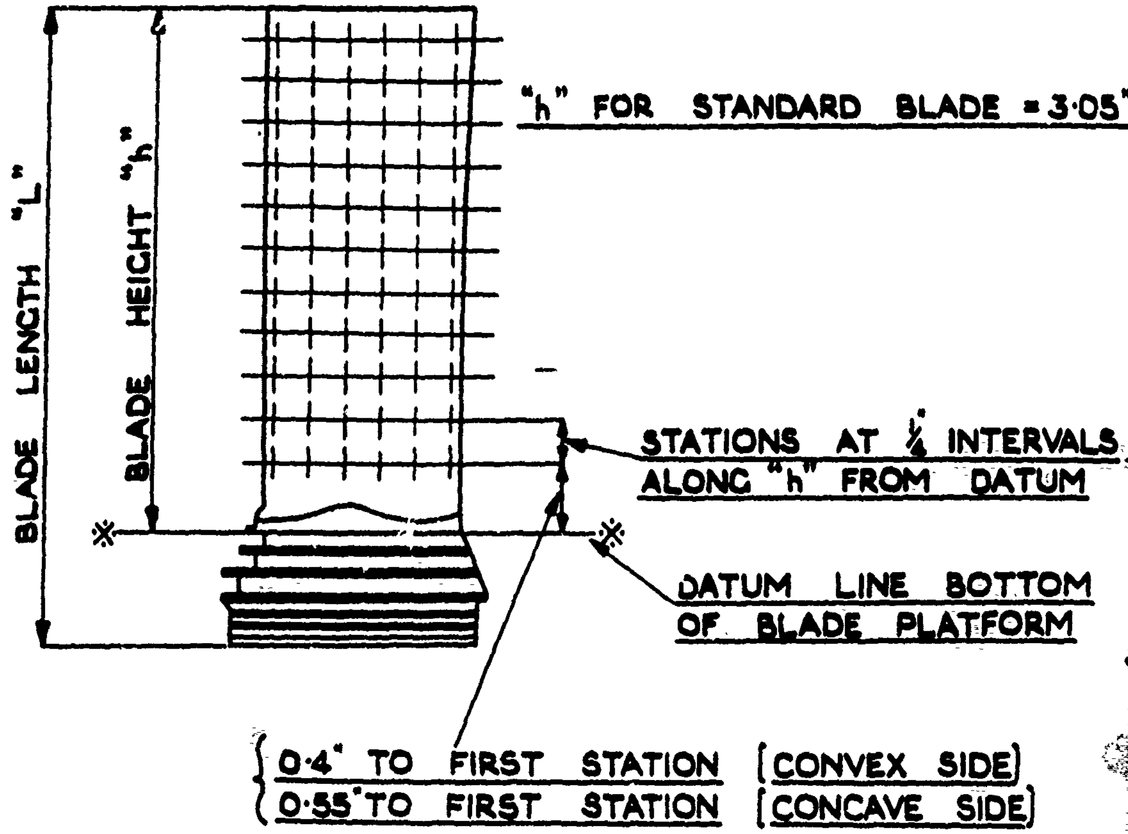
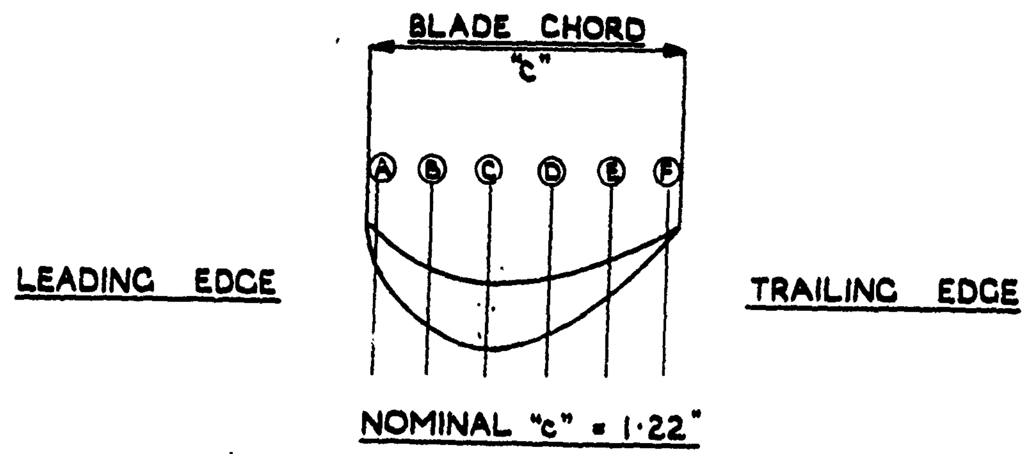
SK 52235

FIG. I.



CHORD STATIONS

STATION	A	B	C	D	E	F
% "c" FROM LEADING EDGE	3·28	24·8	47·2	67·2	82·8	96·7



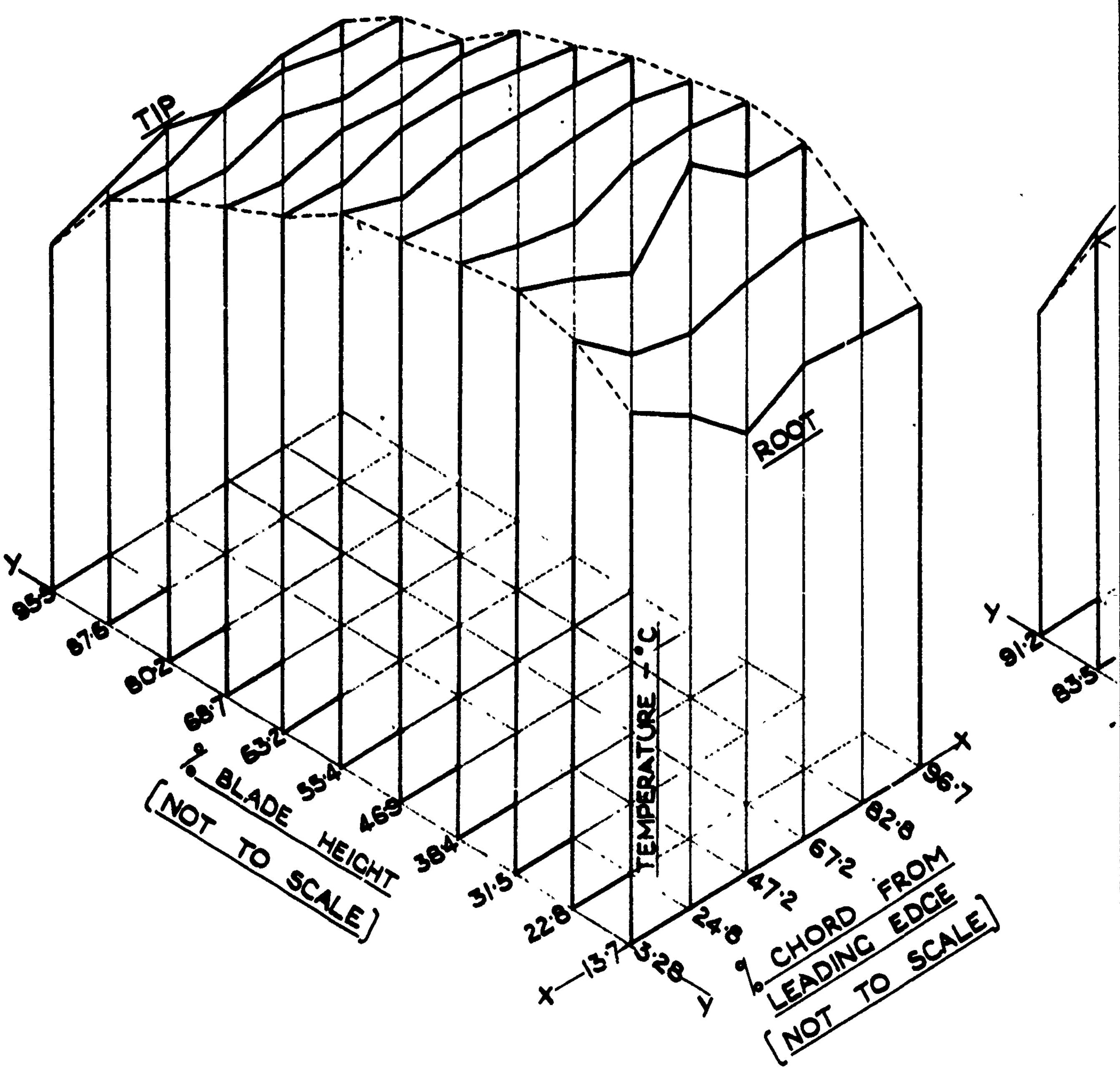
POSITIONS OF V.P.N. READINGS ON W2/700

TURBINE BLADES

SK 52236

WATER FLOW = 0 LB

CONVEX SIDE



TEMPERATURE SCALE :– 1 INCH = 10

DATUM PLANE [XX & YY] REP

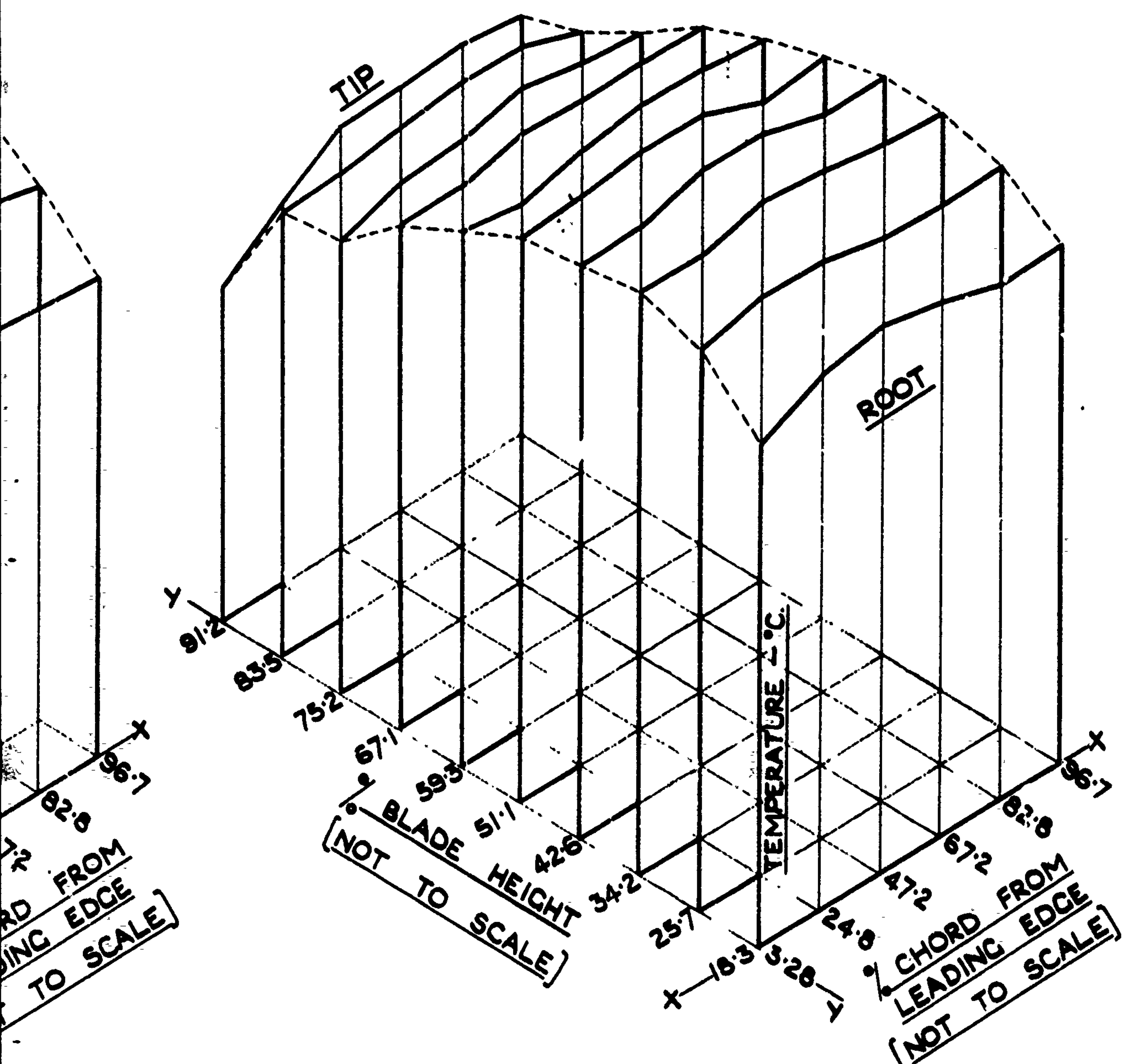
TEMPERATURE PROFILES OF SILVER STEEL BLADES

AT 15,040 R.P.M. & 500°C. JET

1142

ATER FLOW = 0 LB/HR

CONCAVE SIDE



ALE :- 1 INCH = 100° C ABOVE DATUM

ANE [XX & YY] REPRESENTS 200°C.

STEEL BLADES IN W2/700 WITH WATER COOLING

500°C. JET PIPE TEMPERATURE

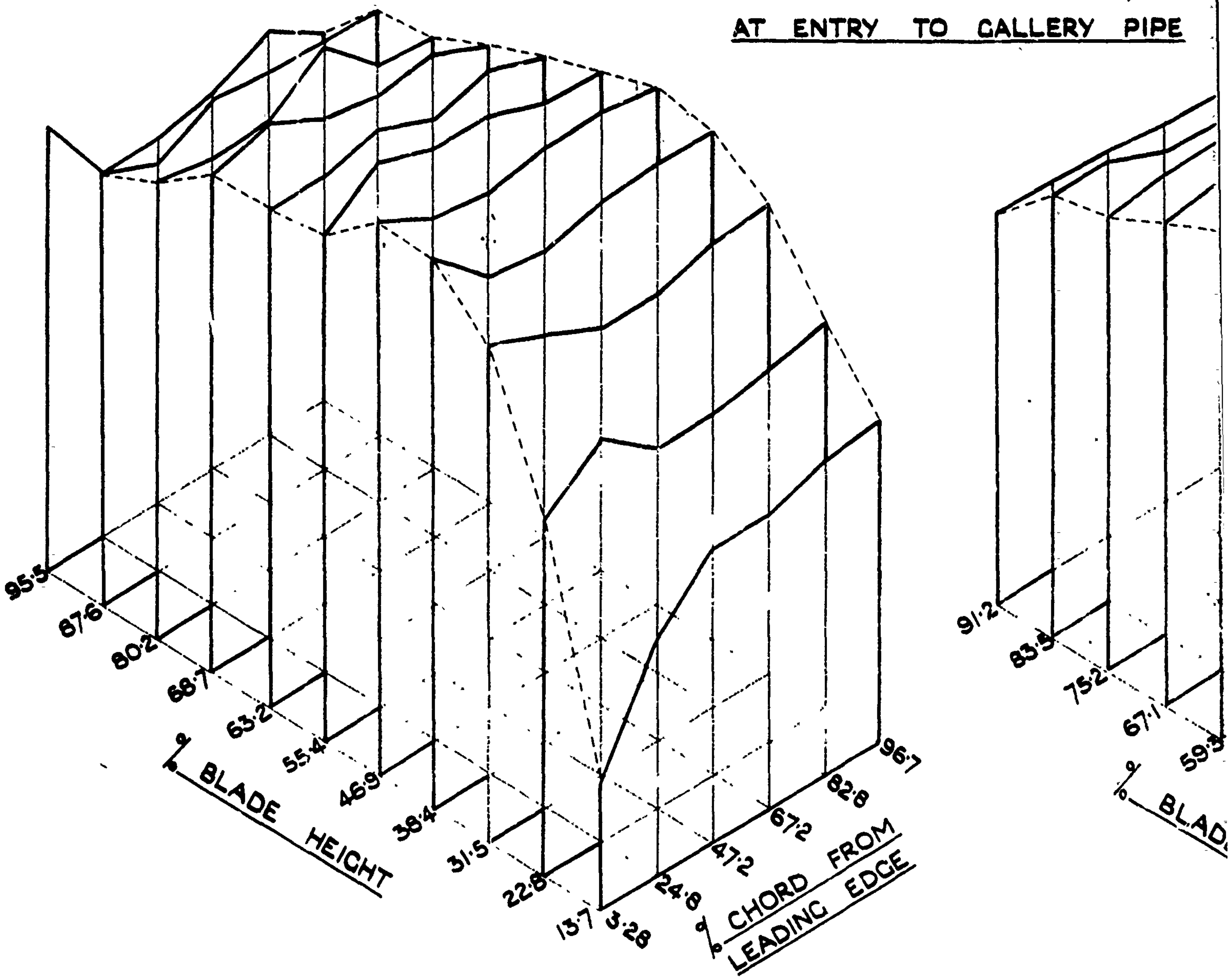
2 of 2

CONVEX SIDE

WATER FLOW = 206 LB/HR

DELIVERY PRESSURE = 11 LB/SQ.IN

AT ENTRY TO GALLERY PIPE



$\frac{\text{WATER}}{\text{FUEL}}$ = 13 %

TEMPERATURE PROFILES OF SILVER STEEL BLADES IN W2

AT 15,040 R.P.M. & 500° C. JET PIPE

1062

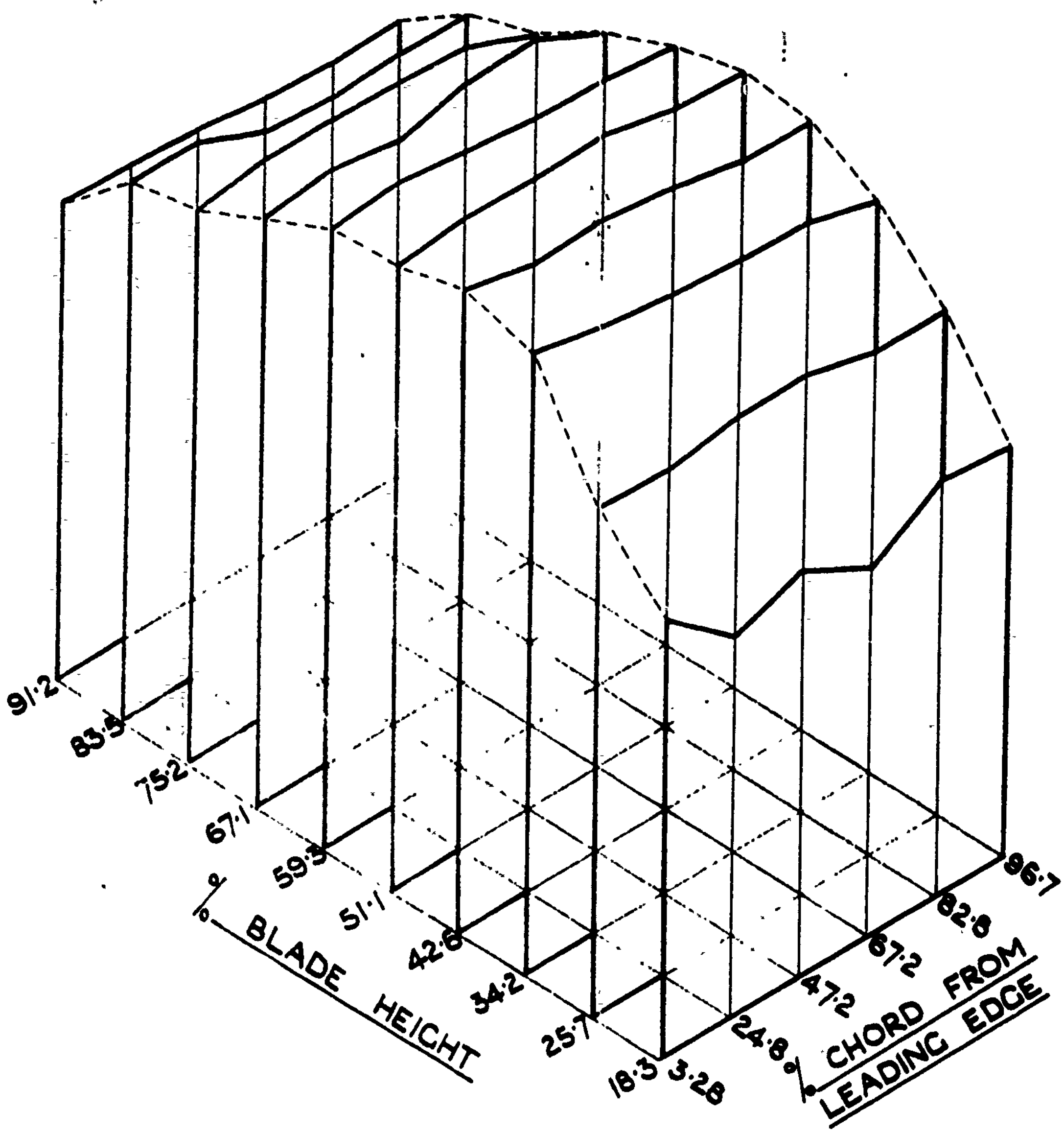
FIG. 5.

W = 206 LB/HR

RESSURE = 11 LB/SQ. IN.

TO GALLERY PIPE

CONCAVE SIDE



BLADES IN W2/700 WITH WATER COOLING

C. JET PIPE TEMPERATURE

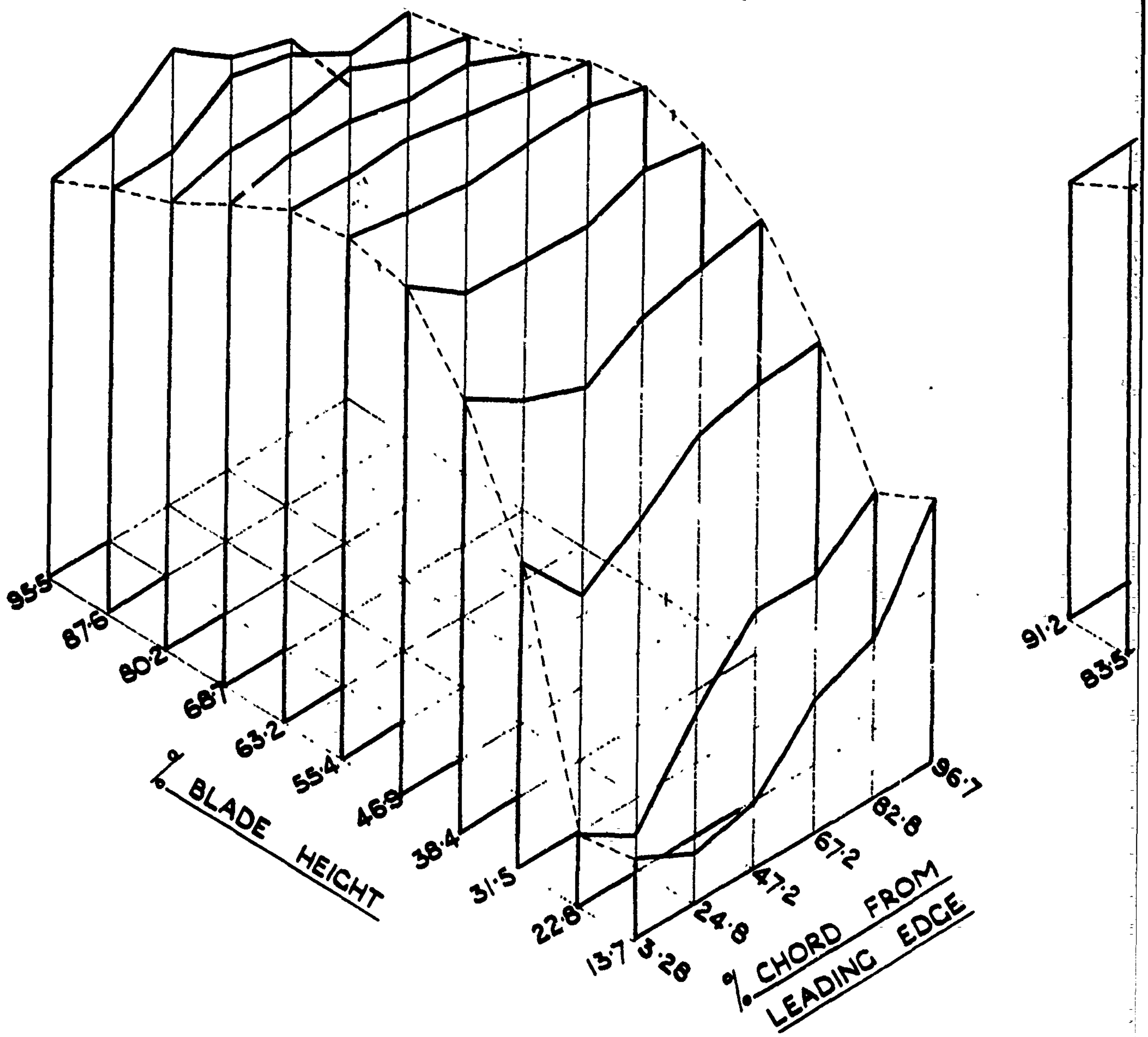
2 of 2

SK 52238

CONVEX SIDE

WATER FLOW = 420 LB

DEL 'VERY PRESSURE = 3.



$\frac{\text{WATER}}{\text{FUEL}} = 24{\cdot}8$

TEMPERATURE PROFILES OF SILVER STEEL BLADES

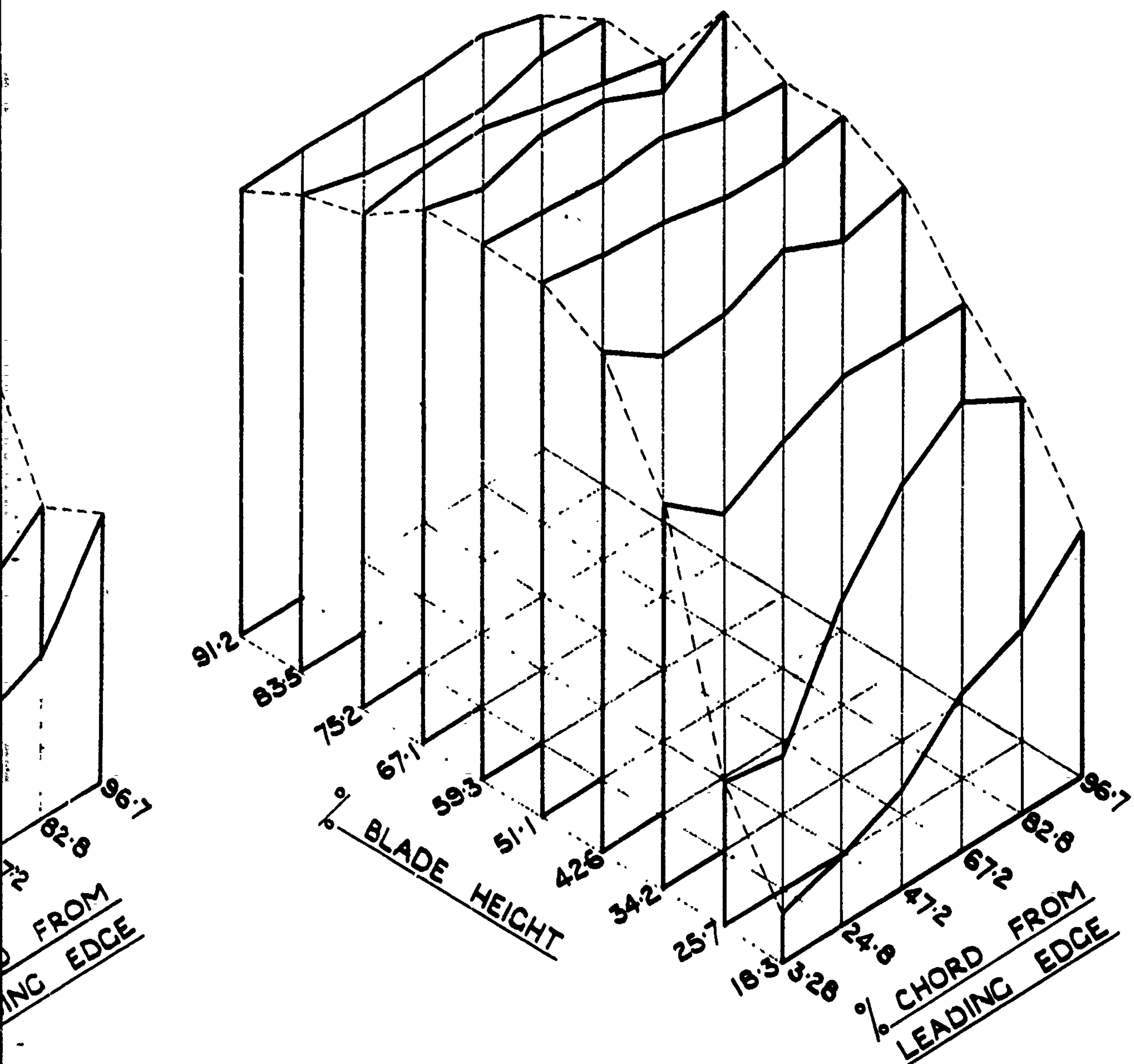
AT 15,040 R.P.M. & 500°C. JET

1082

ER FLOW = 420 LB/HR

/ERY PRESSURE = 33 LB/SQ.IN.

CONCAVE SIDE



$\frac{\text{WATER}}{\text{FUEL}}$ = 24·8 %

STEEL BLADES IN W2/700 WITH WATER COOLING

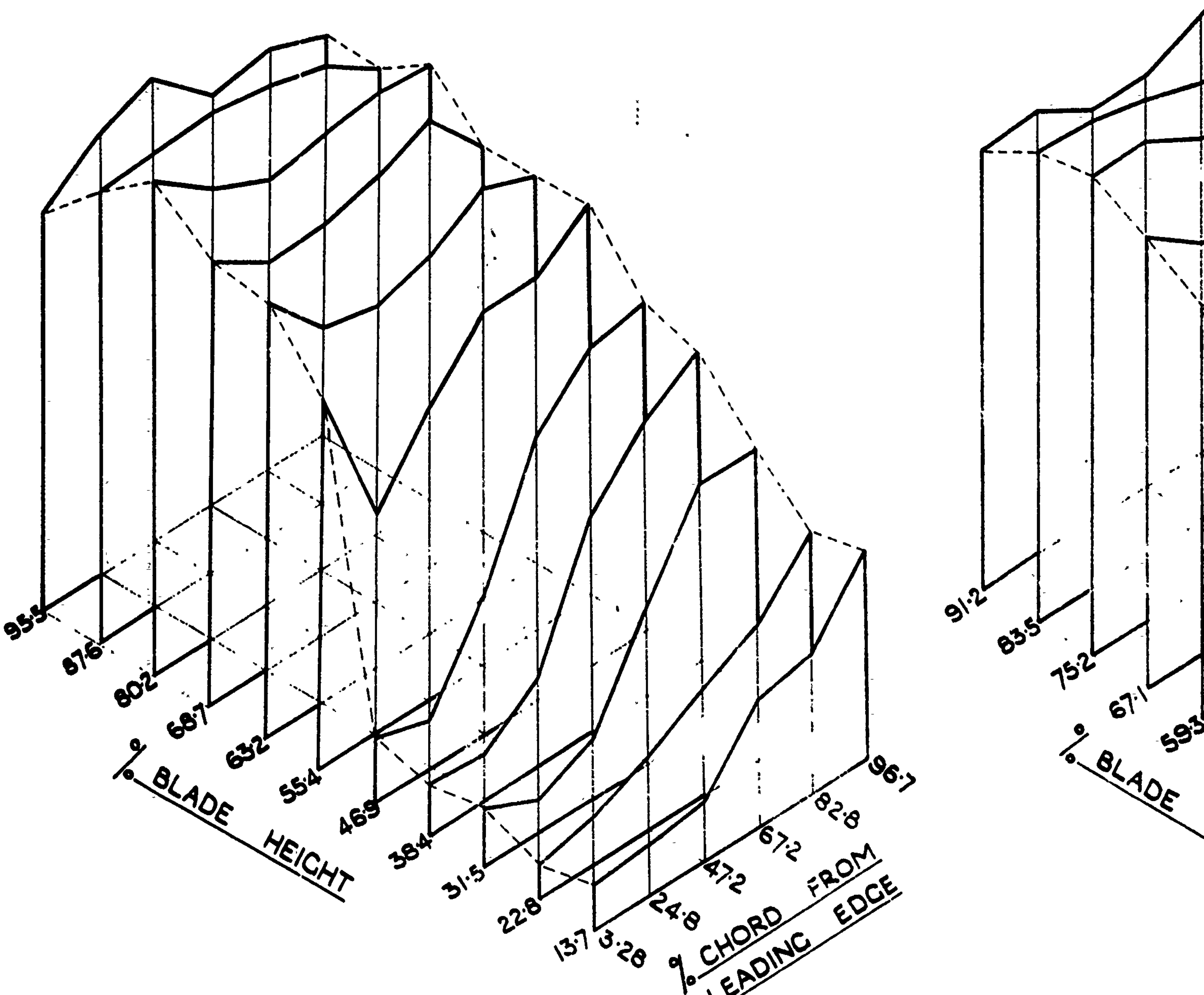
500°C. JET PIPE TEMPERATURE

2 of 2

CONVEX SIDE

WATER FLOW = 618 LB/HR

DELIVERY PRESSURE = 35 LB/SQ.IN.



$\frac{\text{WATER}}{\text{FUEL}} = 38 \cdot 7\%$

TEMPERATURE PROFILES OF SILVER STEEL BLADES IN W2,

AT 15,040 R.P.M. & 500° C. JET PIPE T

1082

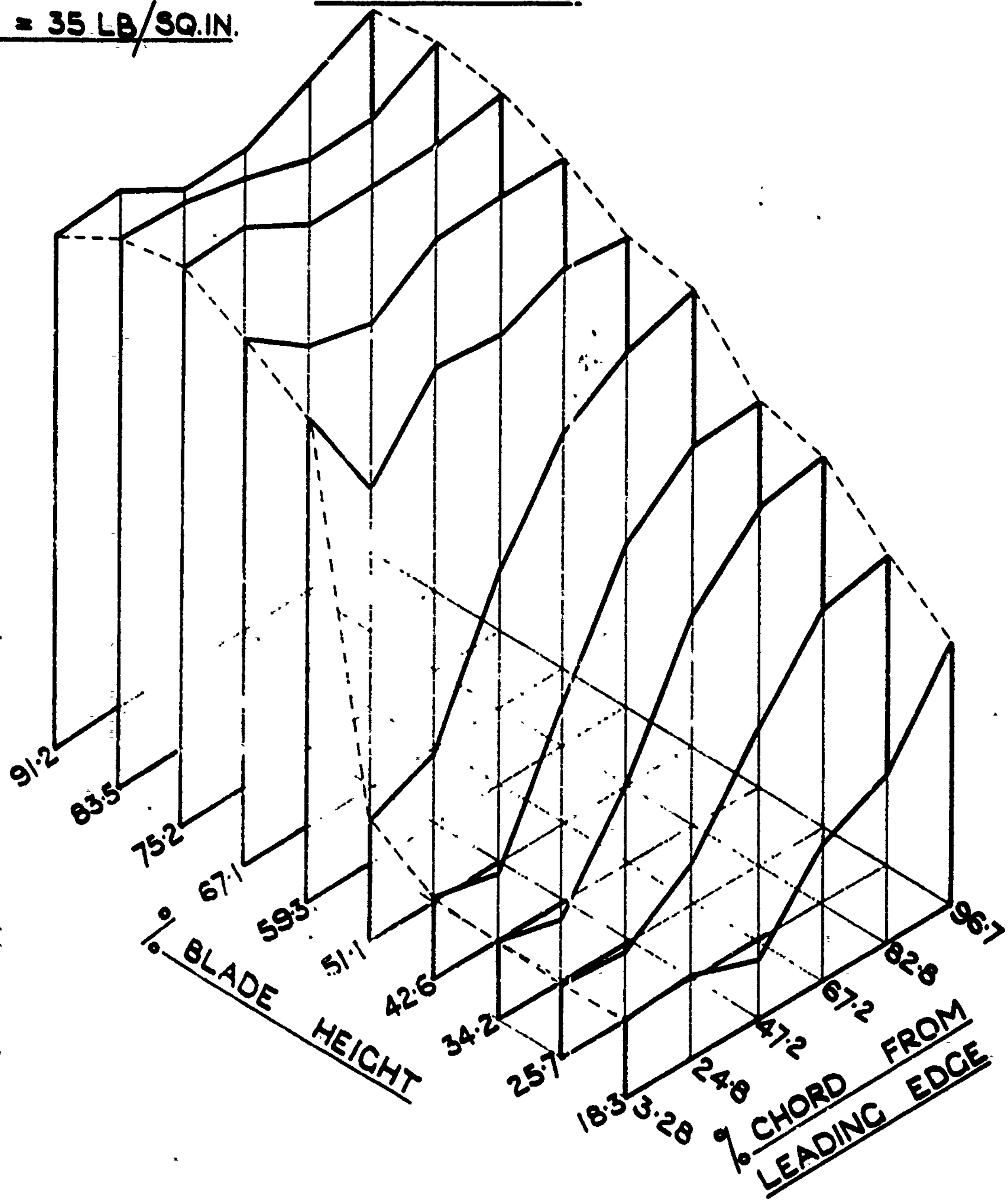
518 LB/HR

FIG. 5.

SK 5223!

E = 35 LB/SQ.IN.

CONCAVE SIDE



58·7%

LADES IN W2/700 WITH WATER COOLING

. JET PIPE TEMPERATURE

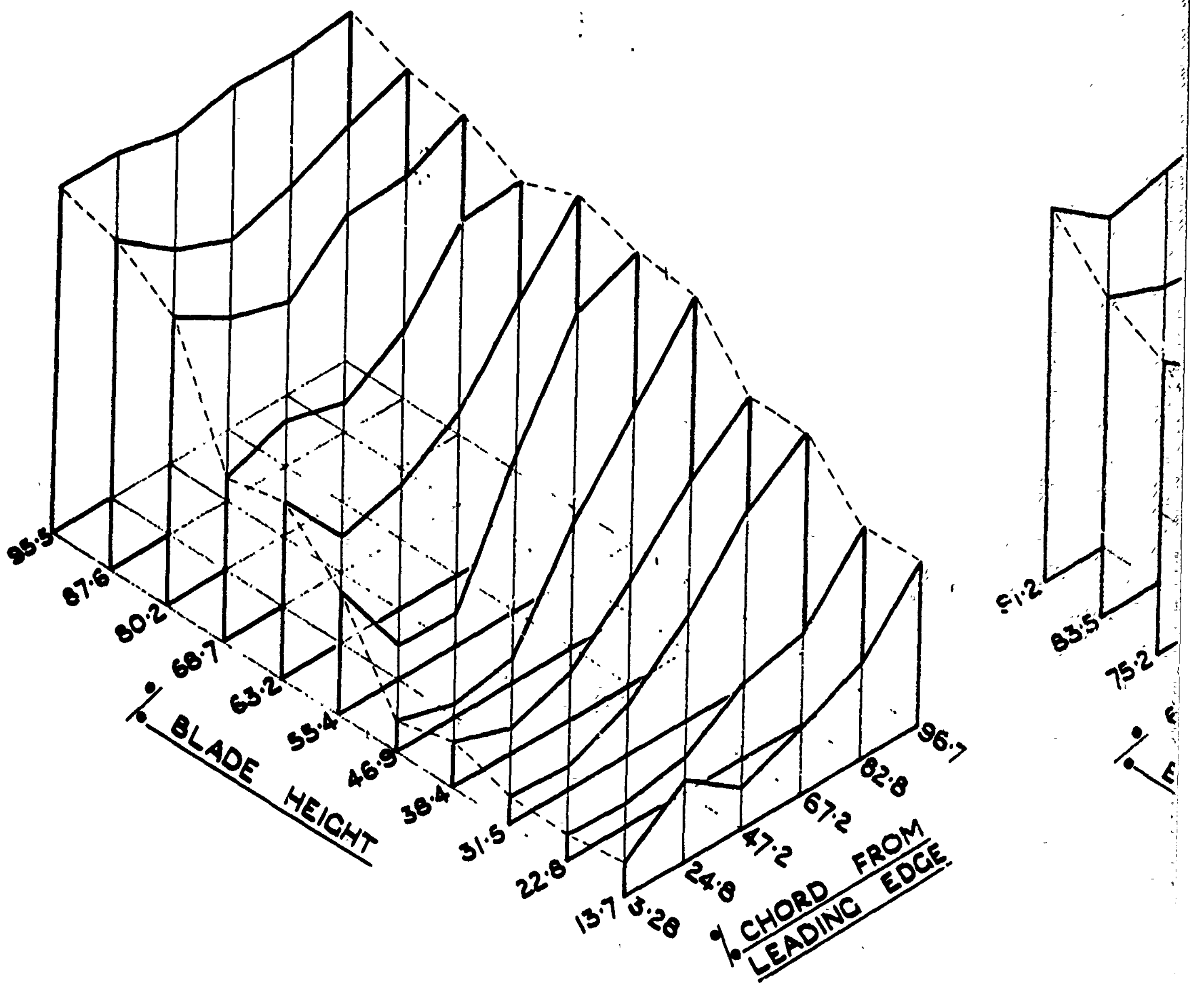
2082

SK 52240

WATER FLOW = 797 LB/HR

DELIVERY PRESSURE 39 LB/S

CONVEX SIDE



$\frac{\text{WATER}}{\text{FUEL}}$ = 50·2 %

TEMPERATURE PROFILES OF SILVER STEEL BLADES IN

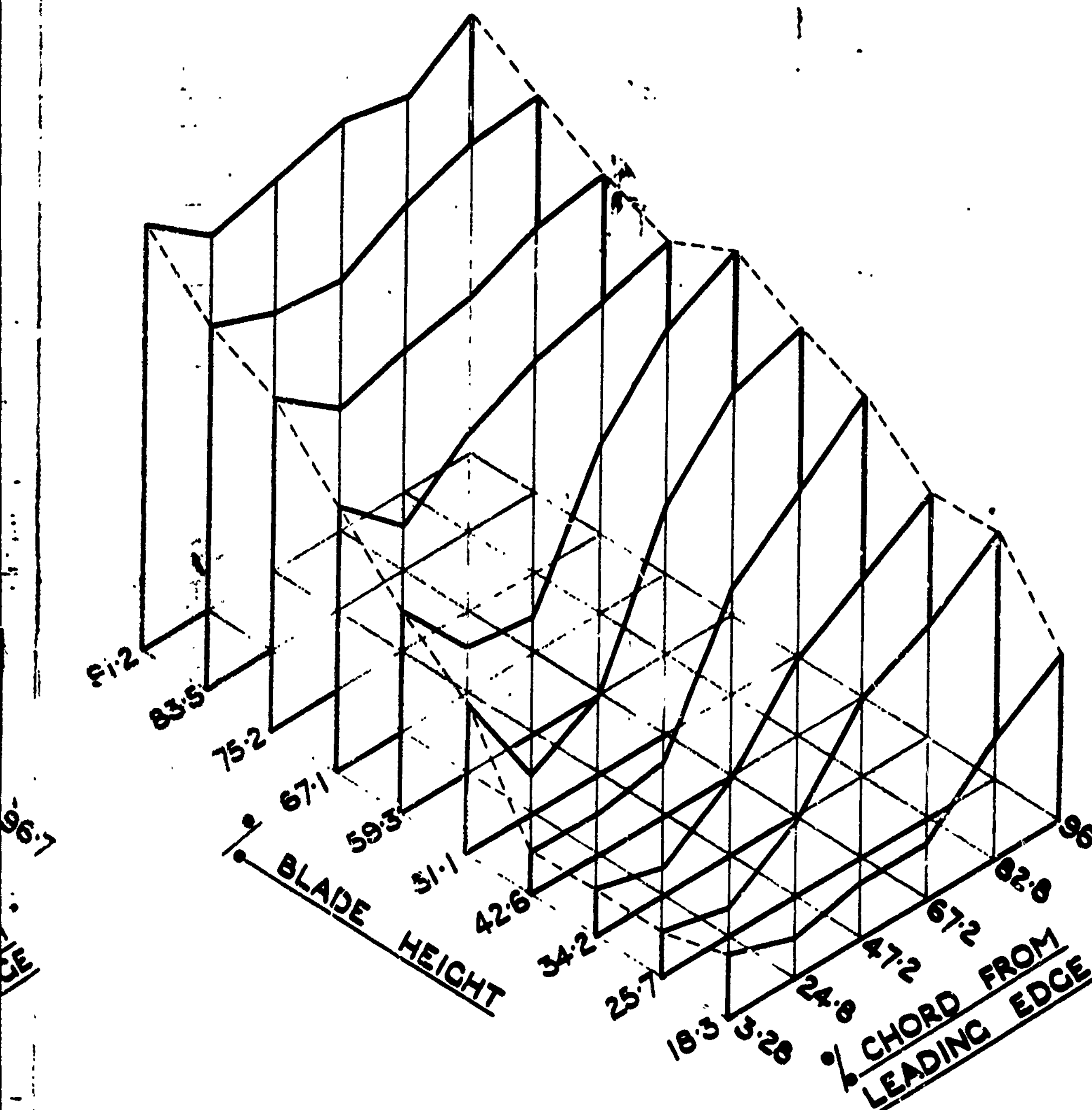
AT 15,040 R.P.M. & 500°C. JET PIP

1082

FIG. 6.

LOW = 797 LB/HR

PRESSURE 39 LB/SQ.IN. CONCAVE SIDE

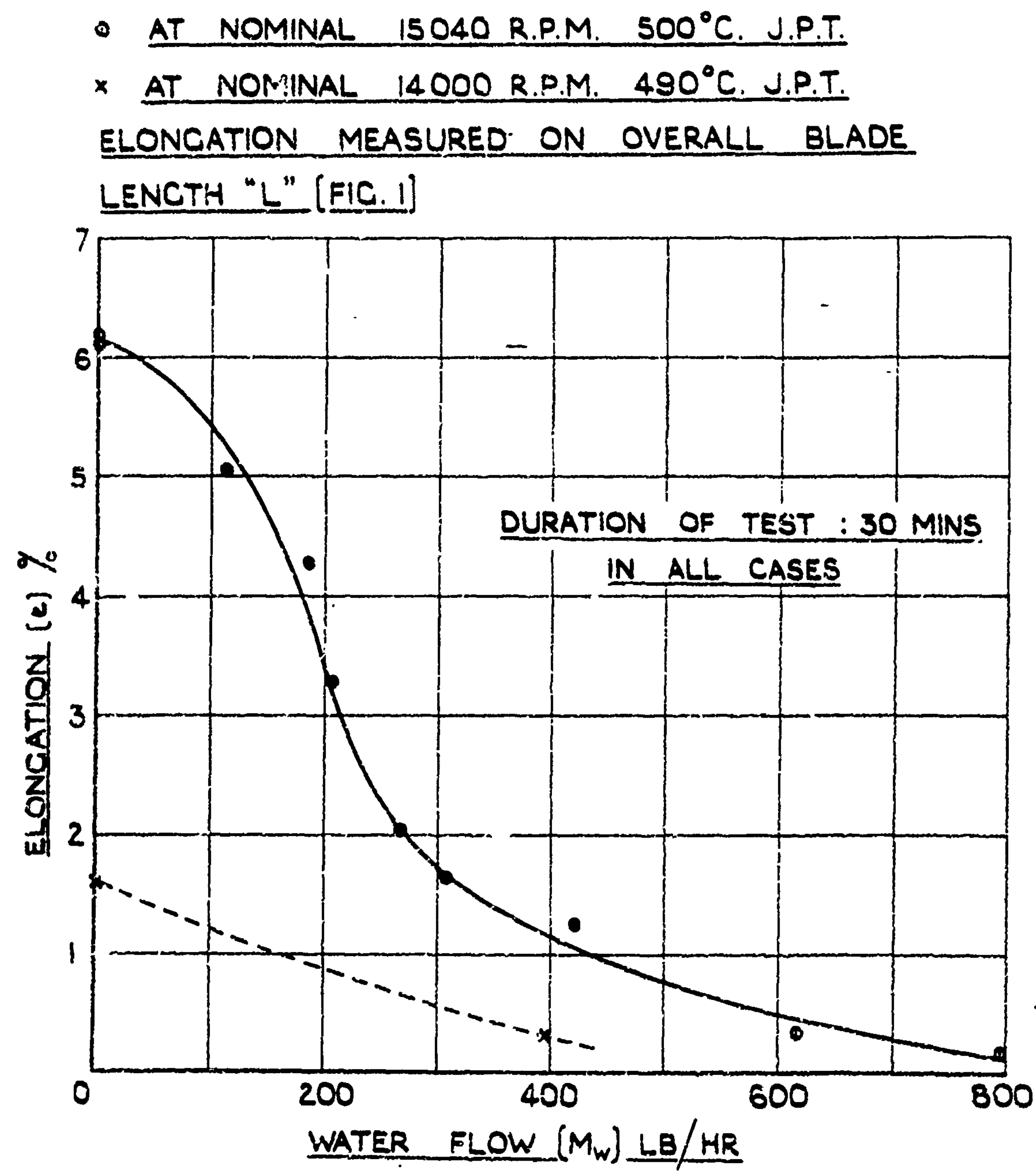


= 50·2%

BLADES IN W2/700 WITH WATER COOLING

FIG. 8.

SK 52241



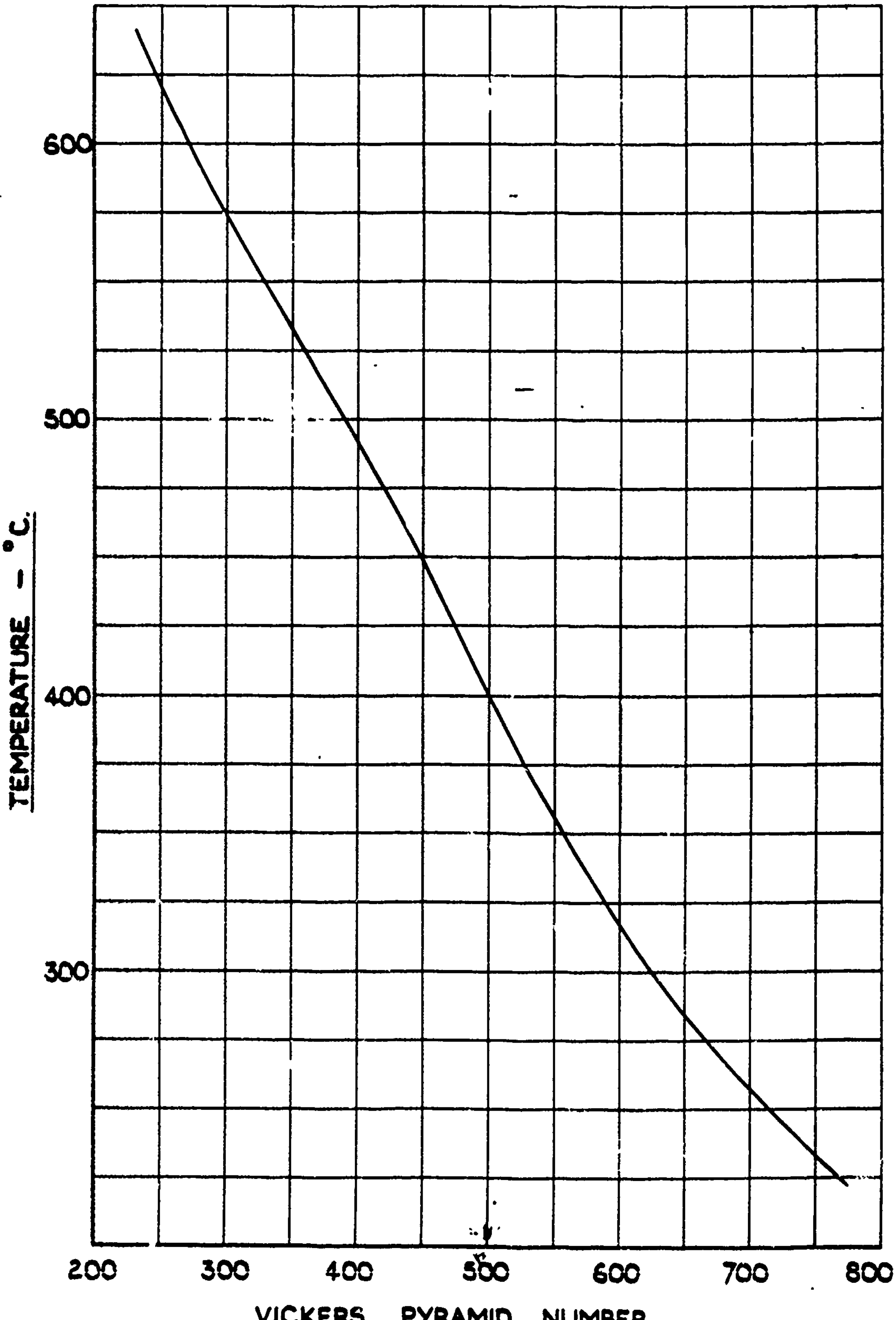
W2/700 SILVER STEEL TURBINE BLADES

PERCENTAGE ELONGATION vs WATER FLOW

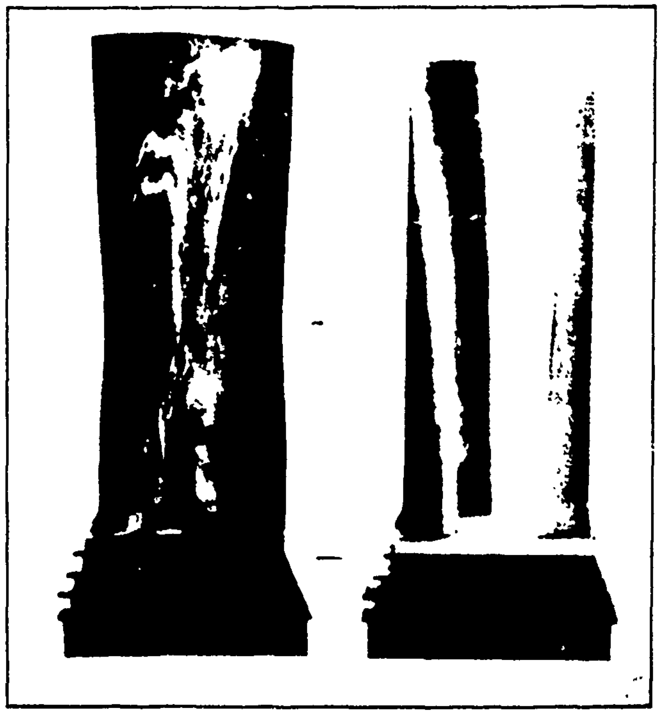
FOR GIVEN R.P.M.

FIG. 9.

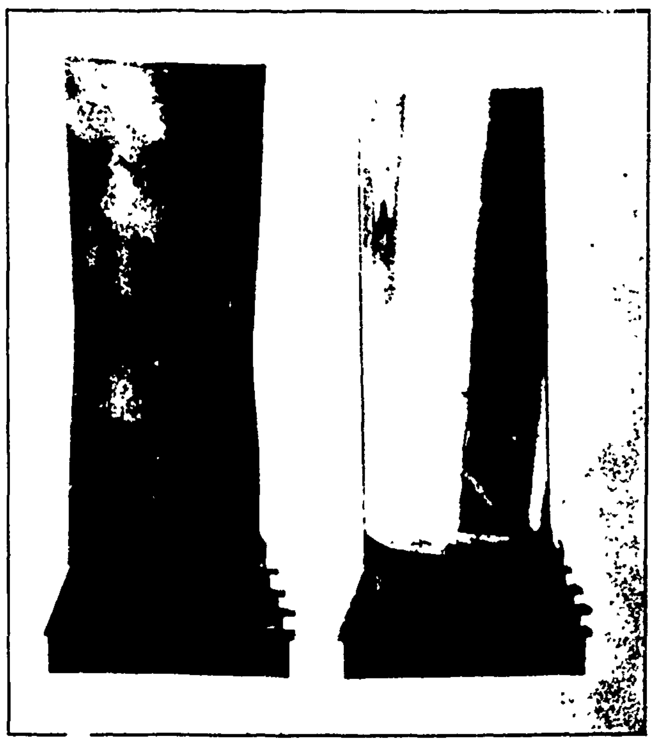
SK 52299



HARDNESS TEMPERATURE CALIBRATION CURVE FOR W2/700 SILVER STEEL TURBINE BLADES



CONVEX SIDE



CONCAVE SIDE

W2/700 SILVER STEEL BLADE BEFORE AND AFTER RUNNING AT 15,040 R.P.M. 500°C JET PIPE TEMPERATURE AND WATER FLOW OF 185 LB/HR

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